

IEEE 802.15.4 MAC Layer Performance Enhancement by employing RTS/CTS combined with Packet Concatenation

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Abstract—IEEE 802.15.4 Medium Access Control (MAC) layer does not include the Request-To-Send/Clear-To-Send (RTS/CTS) handshake mechanism, in order to overcome the hidden node problem that affects Wireless Sensor Networks (WSNs). In this paper we propose and analyse the use of RTS/CTS in IEEE 802.15.4 for the nonbeacon-enabled mode. The proposed solution shows that by considering the RTS/CTS mechanism combined with packet aggregation we improve the network performance in terms of maximum throughput, minimum delay and bandwidth efficiency.

In IEEE 802.15.4 with RTS/CTS, the backoff procedure process is not repeated for each data packet sent like in IEEE 802.15.4 for the basic access mode, but only for each RTS/CTS set. Therefore, the channel utilization is maximized by decreasing the deferral time period before transmitting a data packet.

Our work introduces an analytical model capable of taking into account the retransmission delays and the maximum number of backoff stages. The successful validation of our analytical model is carried out by comparison against simulation results by using the OMNeT++ simulator.

I. INTRODUCTION

In the last years, we have witnessed the growth of the wide range of applications for Wireless Sensor Networks (WSNs) that include ubiquitous monitoring, environmental surveillance, health care, smart grids, etc. IEEE 802.15.4, which defines Physical (PHY) and Medium Access Control (MAC) layers [1], is becoming the reference communication standard providing low-power and low-data-rate communication for Wireless Personal Area Networks (WPANs). Various Working Groups within IEEE are currently putting great effort on developing more effective standards for 802.15.4 [2].

Although, the RTS/CTS (Request-To-Send/Clear-To-Send) scheme is often employed to improve performance as it shortens packet collision duration and addresses the hidden station problem, until now, RTS/CTS is not proposed in any of the IEEE 802.15.4 standards. This reservation scheme actually involves the transmission of the short RTS and CTS control packets prior to the transmission of the actual data packet. However, RTS/CTS decreases efficiency since it transmits two additional control packets without any payload. There are a number of studies in the literature on the performance of

the RTS/CTS reservation mechanism in either IEEE 802.15.4 or 802.11 wireless networks [3]–[6]. Authors in [3] study proposed a broadcasting method based on RTS/CTS for IEEE 802.15.4 network in which the sender node uses a RTS packet to select the receiver node from neighboring nodes. Work in [4] proposes an adaptive mechanism based on RTS/CTS in order to combat the hidden terminal problem in an IEEE 802.15.4 nonbeacon-enabled multi-hop network. Authors in [5] studied the effectiveness of the RTS/CTS scheme in reducing the collision duration for IEEE 802.11 Wireless Local Area Networks (WLANs) under certain scenarios. In a latter work, authors in [6] tried to optimally employ the RTS/CTS scheme by deriving an all-purpose expression for the RTS threshold, a manageable parameter that indicates the data length under which the data packets should be sent without RTS/CTS.

This paper is organized as follows. Section II provides a technical overview of the IEEE 802.15.4 standard (basic access mode) and the timing constraints imposed by the standard itself. Moreover, details about the proposed RTS/CTS reservation scheme are also provided. Furthermore, the theoretical maximum throughput and minimum end-to-end delay limits are derived for both access schemes by taking into account the retransmission delay and the maximum number of backoff stages. Section III addresses the numerical and simulation results to verify the validity of our model and explore the effectiveness of the proposed RTS/CTS scheme that is combined with packet concatenation. Finally, Section IV discusses the conclusions of our work.

II. IEEE 802.15.4 WITH AND WITH NO RTS/CTS

The main reasons why IEEE 802.15.4 basic access mode does not consider the adoption of the RTS/CTS handshake mechanism are the following ones. (i) The introduction of RTS/CTS packets adds additional protocol overhead and, in a situation with low traffic load, short packet sizes could have the same order of magnitude of a RTS/CTS packet. (ii) The absence of a RTS/CTS handshake mechanism allows for reducing the system complexity.

Although these assumptions are true for some particular cases, we argue that in the presence of link layer errors the additional protocol overhead due to the use of RTS/CTS packets is mitigated by our concatenation mechanism. So, there is no need to repeat the backoff procedure for each data packet sent, but only once for each RTS/CTS set. Moreover, by using the proposed RTS/CTS mechanism we avoid packet collisions between the hidden nodes, allowing for decreasing the number of retransmitted packets and, thus, increasing the network performance.

In our proposal, we also assume that both the RTS and CTS packets have the structure of an acknowledgment (ACK) packet, which is assumed to have a limited size of 11 bytes.

A. IEEE 802.15.4 basic access mode

In [7], we have shown that one of fundamental reasons for the IEEE 802.15.4 standard MAC inefficiency is overhead, and we have proposed a mathematical model that derives the throughput and end-to-end delay limits under ideal conditions (a channel environment with no transmission errors). In the scope of this research, we will study the impact of retransmissions in IEEE 802.15.4 basic access mode by considering an erroneous channel. Table I presents the key parameters, symbols and values that we will considered throughout our work. Hence, there is no need to redefine every parameter after every equation.

TABLE I
PARAMETERS, SYMBOLS AND VALUES FOR THE IEEE 802.15.4 STANDARD WITH AND WITH NO RTS/CTS (BASED ON [7]).

Description	Symbol	Value
Backoff period duration	T_{BO}	320 μ s
CCA detection time	T_{CCA}	128 μ s
Setup radio to RX or TX states [8]	$rxSetupTime$	1720 μ s
Time delay due to CCA	$ccaTime$	1920 μ s
TX/RX or RX/TX switching time	T_{TA}	192 μ s
PHY length overhead	L_{H_PHY}	6 bytes
MAC overhead	L_{H_MAC}	9 bytes
DATA payload	L_{DATA}	1 to 112 bytes
DATA frame length	L_{FL}	18 bytes
ACK/RTS/CTS frame length	L_{ACK}	11 bytes
Short Interframe spacing (SIFS) time	T_{SIFS}	192 μ s
Long Interframe spacing (LIFS) time	T_{LIFS}	640 μ s
RTS transmission time	T_{RTS}	352 μ s
CTS transmission time	T_{CTS}	352 μ s
Number of TX frames	n	1 to 100
Number of Aggregated frames	N_{agg}	1 to 100
Retries allowed after a TX failure.	$MaxRet$	2
Data Rate	R	250 kb/s

Data packet collision between neighbouring nodes may occur if two or more nodes during the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) algorithm perform Clear Channel Assessment (CCA) simultaneously, the channel is found to be idle and packet transmissions occur at the same time. In order to characterize the backoff phase (this time period is not generally called contention window in IEEE 802.15.4) we consider the same as the one from the model presented in [9].

As shown in Figure 1.a), for each transmission attempt in the

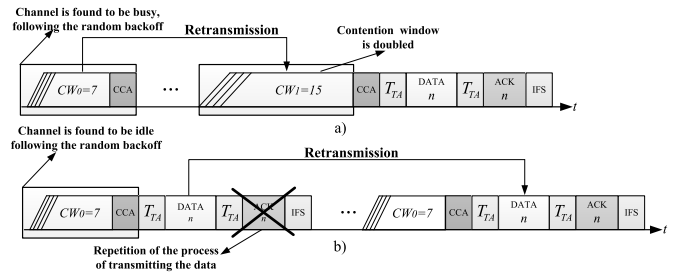


Figure 1. IEEE 802.15.4 basic access mode with retransmissions: a) channel is found to be busy and b) channel is found to be idle.

basic access mode from IEEE 802.15.4, nodes perform a random backoff from a uniform distribution over $[0, CW]$, where CW is the contention window. The $CW_{NB} = [2^{BE_i} - 1]$ represents the backoff delay before performing CCA. The backoff exponential value, BE_i , depends on the backoff stage at slot t , $BO_s(t)$. After performing CCA, if the channel is found to be idle a data packet transmission takes place. Otherwise, if the channel is found to be busy, nodes will defer data transmission for a random backoff period defined by the next backoff stage. The backoff contention window is doubled whenever the channel is determined busy during CCA until it reaches its maximum value and cannot be increased any further [9]. Then, the backoff window remains the same until the maximum retry limit is reached (e.g., $NB_{max} = 4$) [10]. In the last retransmission case, if the channel is found to be busy, and nodes cannot succeed in sending the packet, the packet will be discarded from the MAC queue. Then, a new transmission cycle will start, with a backoff delay defined by BE_0 (e.g., $CW_0 = 7$) for the next data packet to be transmitted, and the same CSMA-CA algorithm will be repeated. Table II presents the different values for the backoff stages and the corresponding CW_{NB} by assuming the combination pair $NB_{max} = 4$ and $BE_{max} = 5$.

TABLE II
BACKOFF STAGES FOR IEEE 802.15.4.

NB	BO_s	BE_i	$CW_{NB} = [2^{BE_i} - 1]$	\overline{CW}_{NB}
0	0	3	$CW_0 = 7$	3.5
1	1	4	$CW_1 = 15$	7.5
2	2	5	$CW_2 = 31$	15.5
3	3	5	$CW_3 = CW_2 = 31$	15.5
4	4	5	$CW_4 = CW_2 = 31$	15.5

If, the channel is found to be idle during CCA following the backoff phase, and an ACK is not received within the ACK wait duration period, T_{AW} , nodes shall consider that the transmission attempt has failed. In this case, nodes shall repeat the DATA/ACK handshake process and the backoff window is given by the first backoff phase (i.e., first contention window, CW_0), as shown in Figure 1.b).

In an erroneous channel, to determine the maximum average throughput, S_{max} , first it is important to determine the minimum average delay, D_{min} . The D_{min} , is obtained by taking into account the channel state (i.e., idle or busy) during CCA

and the number of retransmissions for the non-received ACK control packets, by considering packet collisions and channel errors. In IEEE 802.15.4 basic access mode, the minimum delay due to CCA, D_{min_CCA} , is given as follows:

$$D_{min_CCA} = \sum_{i=1}^n \sum_{k=0}^{k \leq NB} (\overline{CW_k} + ccaTime) \quad (1)$$

where $NB \in [0, NB_{max}]$.

Equation (1), provides the minimum delay, resulting from the number of times the channel state (i.e., busy or idle) is determined during CCA. Every time the channel is found to be busy both NB and BE are increased by 1, as shown in Table II. When BE reaches its maximum value, there is no more increase. By analysing Table II, we conclude that, when $BO_s = 4$, and by considering $NB = NB_{max} = 4$, the BE cannot be increased any further. If $NB > NB_{max}$ the CSMA-CA algorithm will finish by entering in the "Failure" state, which means that the node does not succeed in accessing the channel. Equation (1) also accounts each transmitted packet ranging from 1 to n , where n represents the total number of transmitted packets for each active period. The number of times the CW will be doubled for each transmitted packet depends on the channel state determined during CCA (i.e., busy or idle).

The minimum delay due to packet retransmissions, $D_{min_DataRet}$, when the channel is found to be idle during CCA, after the backoff phase, where there is a data transmission and an ACK is not received within the ACK wait duration period, defined by T_{AW} , is given as follows:

$$D_{min_DataRet} = \sum_{i=1}^n K_i$$

$$K_i = \begin{cases} H_1 & , j = 0 \\ H_2 + (j - 1) \times H_4 + H_3 & , j \in [1, MaxRet] \end{cases} \quad (2)$$

where j is the number of packet retransmissions, and could range between 0 and the maximum number of retransmissions, like in [10]. By analysing equation (2), we reach the following conclusions:

- If, after CCA, nodes determine that the channel is found to be idle and an ACK is correctly received following the transmission of a data packet, the minimum delay, $D_{min_DataRet}$, is given by:

$$H_1 = T_{TA} + T_{DATA} + T_{TA} + T_{ACK} + T_{IFS} \quad (3)$$

The number of packet retransmissions for this case is given by $j = 0$. It is worthwhile to mention that, since we are considering the minimum delay, there is no need to consider the ACK wait duration period, T_{AW} , in the equation, which represents the longest time needed for receiving an ACK control packet;

- If, after CCA, nodes determine that the channel is found to be idle and an ACK is not correctly received following the transmission of a data packet, in which the node only

tries to retransmit a packet once (i.e., $j = 1$), the minimum delay due to packet retransmissions, $D_{min_DataRet}$, is given by $H_2 + H_3$, where:

$$H_2 = T_{TA} + T_{DATA} + T_{AW} \quad (4)$$

$$H_3 = \overline{CW_0} + ccaTime + H_1 \quad (5)$$

The term H_2 indicates that in the first transmission attempt no ACK has been received within T_{AW} . The term H_3 indicates that nodes only received an ACK control packet after retransmitting the packet one more time. The packets are retransmitted by considering the first contention window (CW_0) defined by the CSMA-CA algorithm [10];

- If, the number of retransmission attempts is more than one, it means that a node has failed to previously retransmit a packet and it will retry to transmit a packet until the number of maximum retransmissions, $MaxRet$ has been reached. The minimum delay due to packet retransmissions, $D_{min_DataRet}$, is given by:

$$H_2 + (j - 1) \times H_4 + H_3 \quad (6)$$

where, $H_4 = \overline{CW_0} + ccaTime + H_2$. The term $(j - 1) \times H_4$, indicates that the packet will be retransmitted by considering the first contention window in the range $j \in [2, MaxRet]$, and an ACK control packet will be correctly received in the last retransmission attempt given by H_3 .

By combining equations (1) and (2), the minimum average delay, D_{min} , due to the channel state (i.e., busy or idle) and packet retransmissions is given by:

$$D_{min} = (D_{min_CCA} + D_{min_DataRet})/n \quad (7)$$

In IEEE 802.15.4 basic access mode, if an erroneous channel is considered, the maximum average throughput, S_{max} , in bits per second, by considering packet retransmissions is given by:

$$S_{max} = 8L_{DATA}/D_{min} \quad (8)$$

B. IEEE 802.15.4 employing RTS/CTS

In IEEE 802.15.4 with RTS/CTS enabled, nodes will use the same backoff procedure like IEEE 802.15.4 basic access mode. However, this process is not repeated for each data packet sent, but only for each RTS/CTS set. Therefore, the channel utilization is maximized by decreasing the deferral time period before transmitting a data packet, as shown in Figure 2. The minimum delay due to CCA, $D_{min_CCA_RTS}$ for determining if the channel is found to be busy or idle, after the backoff phase, and before each RTS/CTS set is given by:

$$D_{min_CCA_RTS} = \sum_{i=1}^{n/N_{agg}} \sum_{k=0}^{k \leq NB} (\overline{CW_k} + ccaTime) \quad (9)$$

By analysing equation (9), we can conclude that nodes only determine the channel state once per RTS/CTS. Therefore, if a node has $n = 100$ data packets to send and the number of aggregated packets is equal to $N_{agg} = 10$, nodes only determine

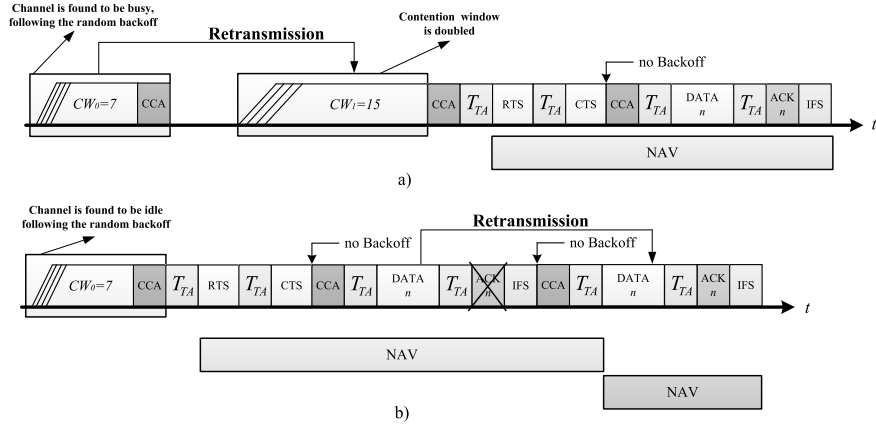


Figure 2. IEEE 802.15.4 with RTS/CTS with retransmissions: a) channel is found to be busy and b) channel is found to be idle.

the channel state 10 times ($n/N_{agg} = 100/10 = 10$) plus the time need for transmitting the packets (until the maximum retry limit, $NB_{max} = 4$, is reached).

If the channel is found to be idle during CCA and, after sending a data packet an ACK is not received within a duration of T_{AW} , the retransmission process will not consider the use of the backoff phase between two consecutive data packets, which allows to decrease the total overhead (as shown in Fig 2.b). Since any other stations can receive both the RTS, CTS, DATA or ACK packets, in the first transmission attempt they will set an internal timer called Network Allocation Vector (NAV) that is responsible for defining the time period a node will defer the channel access in order to avoid collisions.

In the IEEE 802.15.4 MAC protocol with RTS/CTS, the minimum delay due to packet retransmissions, $D_{minDataRetRTS}$, when the channel is found to be idle during CCA, after the backoff phase, there is a data transmission and an ACK is not received within T_{AW} duration, is given as follows:

$$D_{minDataRetRTS} = \begin{cases} H_5 & , \text{ for } j = 0 \\ H_6 & , \text{ for } j \in [1, MaxRet] \end{cases} \quad (10)$$

where j is the number of packet retransmissions (RTX), and varies between 1 and $MaxRet$, as defined in [10]. The following lessons can be learned from the analysis of equation (10):

- If, after CCA, a node determines that the channel is found to be idle, and an ACK is correctly received for each packet sent, the minimum delay, $D_{minDataRetRTS}$, is determined by:

$$H_5 = T_{TA} + T_{RTS} + T_{TA} + T_{CTS} + \dots + \sum_{i=1}^{N_{agg}} (ccaTime + T_{TA} + T_{DATA} + T_{TA} + \dots + T_{ACK} + T_{IFS}) \quad (11)$$

which means that, there are no transmission errors. For this case, the number of retransmissions is given by $j = 0$;

- If after CCA, a node finds the channel to be idle and an ACK has not been received within the duration of T_{AW} , for one or more packets sent (by considering aggregation), the minimum delay due to packet retransmissions, $D_{minDataRetRTS}$, is determined by:

$$H_6 = T_{TA} + T_{RTS} + T_{TA} + T_{CTS} + \dots + \sum_{i=1}^{N_{agg}-m} (ccaTime + T_{TA} + T_{DATA} + T_{TA} + \dots + T_{ACK} + T_{IFS}) + \sum_{i=1}^m (j_i) \times (ccaTime + T_{TA} + T_{DATA} + T_{AW}) + \sum_{i=1}^m (ccaTime + \dots + T_{TA} + T_{DATA} + T_{TA} + T_{ACK} + T_{IFS}) \quad (12)$$

The term $\sum_{i=1}^{N_{agg}-m} (ccaTime + T_{TA} + T_{DATA} + T_{TA} + T_{ACK} + T_{IFS})$ represents the $(n-m)$ transmitted packets that have successfully received an ACK response, where m denotes the number of transmitted packets that need retransmission. Since each individual packet can be retransmitted more than once due to the fact that an ACK has not been received within T_{AW} duration, the term j_i , represents the number of times a packet has experienced retransmission until $MaxRet$ has been reached. We then assume that the ACK packet is received, which represents the last case given by: $\sum_{i=1}^m (ccaTime + T_{TA} + T_{DATA} + T_{TA} + T_{ACK} + T_{IFS})$.

By combining equations (9) and (10), the minimum average delay, $D_{min_RTS_CTS}$, due to the channel state (i.e., busy or idle) and packet retransmissions is given by:

$$D_{min_RTS_CTS} = \frac{D_{min_CCA_RTS} + D_{minDataRetRTS}}{n} \quad (13)$$

III. SIMULATION EVALUATION

We have evaluated IEEE 802.15.4 with and with no RTS/CTS by using the MiXiM simulation framework [11] from the OMNeT++ simulator. A two-hop network topology, with two sources, one relay, two sinks, and two interferers is considered. Packets flow from source node 1, through node 0, to sink node 3, while the packets originated by source node 2 flow, through node 0, to reach sink node 4. This topology is a simple star topology where node 0 acts as a central node. The interferer nodes 5 and 6 are responsible for sending broadcast packets that will collide with the ACK packets being sent by both the sources and the central node. The maximum average throughput, S_{max} , and the minimum average delay, D_{min} , have been obtained through simulation by considering five different seeds, and a 95% confidence interval. Table I presents the MAC parameters considered for the network in our simulations. The performance analysis of the proposed schemes is conducted for both the best-case scenario and by assuming an erroneous channel. A fixed payload size of 3 bytes (i.e., $L_{DATA} = 3$ bytes) is considered. In [12] the authors have shown that for shorter packet sizes IEEE 802.15.4 results in lower bandwidth efficiency, delay and throughput. Therefore, we will simulate the worst case scenario for wireless sensor networks, showing that our proposed mechanism even under these circumstances can improve channel efficiency.

Figure 3 presents the minimum average delay versus the number of transmitted (TX) packets, by considering IEEE 802.15.4 with and with no RTS/CTS, as presented in Figures 1 and 2.

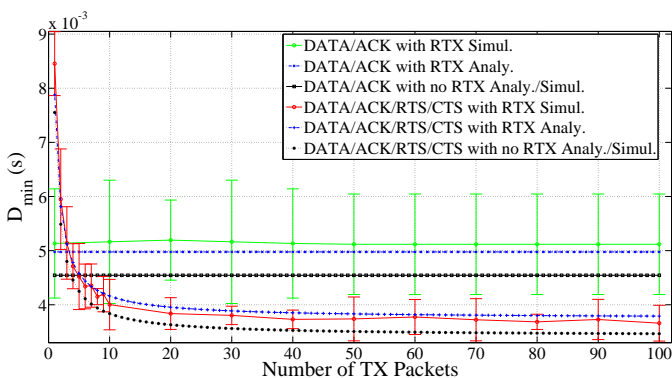


Figure 3. Minimum average delay for IEEE 802.15.4 with and with no RTS/CTS as a function of the number of TX packets.

By analysing Figure 3, we conclude that by varying the number of TX packets, n , between 1 and 100, IEEE 802.15.4 basic access mode with no RTS/CTS globally presents the worst performance in terms of minimum average delay, D_{min} , for both the cases with and with no retransmissions. By comparing the case with no retransmissions with the one presented in [12], we conclude that the differences in terms of minimum average delay, D_{min} , are justified by the fact that the authors in [12] have not considered the time needed to switch the radio between the different states (i.e., $rxSetupTime$) [8]. The standard deviation shown in the simulations is explained

by the fact that nodes will backoff for a random duration of time before attempting to access the channel later on, as presented in equation (1). Besides, if the channel is found to be busy for each TX packet, nodes will double the backoff time counter during the backoff phase and the process is repeated until the maximum contention window is reached.

By considering IEEE 802.15.4 basic access mode with RTS/CTS, combined with the packet concatenation feature, if the number of aggregated packets is higher than 5, IEEE 802.15.4 with RTS/CTS outperforms IEEE 802.15.4 with no RTS/CTS in terms of delay. This is explained by the fact that the backoff phase is not repeated for each transmitted data packet, but only for each RTS/CTS set. Then, there is no backoff phase between two consecutive data packets, which allows for decreasing the total overhead, as shown in Figures 2.a) and b). For the case with retransmissions, since all the packets include the NAV duration, when nodes receive a packet that is not intended for them, they will avoid sending packets as long as this time has not expired. The retransmission process does not include the backoff phase like in the IEEE 802.15.4 basic access mode (i.e., $BE = 0$). By comparing the analytical and simulation results, we conclude that the theoretical results are very similar and this actually verifies the accuracy of our proposed retransmission model. Performance results for D_{min} as a function of the number of TX packets show that, by using IEEE 802.15.4 with RTS/CTS with packet concatenation, for 5 and 10 aggregated packets, D_{min} decreases 8 % and 18 %, respectively. For a number of aggregated packets more than 28, D_{min} decreases approximately 30 %.

Figure 4 presents the maximum average throughput, S_{max} , as a function of the number of TX packets.

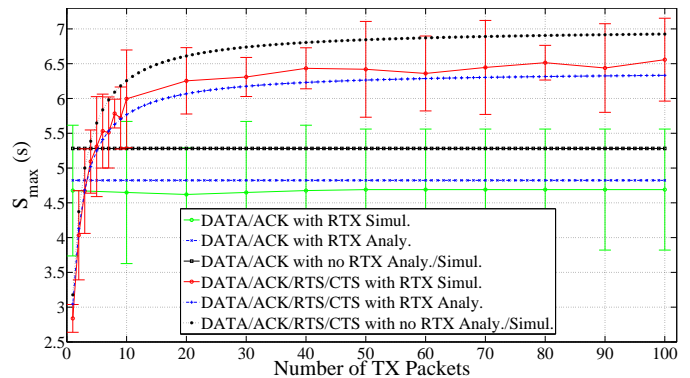


Figure 4. Maximum average throughput for IEEE 802.15.4 with and with no RTS/CTS as a function of the number of TX packets.

By analysing Figure 4, we conclude that for the shortest payload sizes (i.e., $L_{DATA} = 3$), it is possible to improve the network performance by using the proposed RTS/CTS mechanism with packet concatenation. When the number of TX packets exceeds 5, IEEE 802.15.4 with RTS/CTS with and with no retransmissions, achieves higher throughput in comparison to IEEE 802.15.4 with no RTS/CTS. Moreover, we observe that by considering IEEE 802.15.4 in the basic access mode, S_{max} does not depend on the number of TX packets,

and achieves the maximum value of 5.2 kb/s. For IEEE 802.15.4 with RTS/CTS combined with the packet concatenation feature, the maximum achievable throughput is 6.3 kb/s. Results for S_{max} as a function of the number of TX packets in IEEE 802.15.4 with RTS/CTS with packet concatenation show that, for 5 and 10 aggregated packets, S_{max} increases 8 % and 20 %, respectively. For a number of aggregated packets higher than 28, S_{max} increases approximately 30 %.

In order to obtain the bandwidth efficiency, η , of IEEE 802.15.4 with and with no RTS/CTS like the authors from [13] we have used the following equation:

$$\eta = \frac{S_{max}}{R} \quad (14)$$

where, R , is the maximum data rate.

Figure 5 presents the bandwidth efficiency versus the number of TX packets.

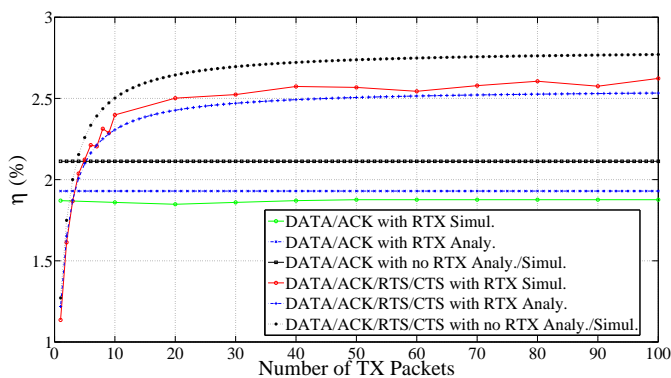


Figure 5. Bandwidth efficiency as a function of the number of TX packets.

By analysing Figure 5, we can observe that for IEEE 802.15.4 with no RTS/CTS and with and with no retransmissions, the bandwidth efficiency is 1.9 % and 2.1 %, respectively. The channel efficiency remains constant by varying the number of TX packets. The results show that in the case with no retransmissions, the obtained results are very similar to the ones obtained in [12] and [13], which again shows the appropriateness of the proposed analytical formulation.

For IEEE 802.15.4 with RTS/CTS and with and with no retransmissions, the bandwidth efficiency is dependent on the number of TX packet (by considering aggregation). The results show, that by aggregating more than 5 packets IEEE 802.15.4 with RTS/CTS outperforms IEEE 802.15.4 with no RTS/CTS, in terms of bandwidth efficiency, η , where the maximum achievable value is 2.8%.

Based on the results, we can conclude that even for shortest packet sizes (i.e., $L_{DATA} = 3$), by using the proposed RTS/CTS mechanism with packet concatenation it is possible to improve channel efficiency.

IV. CONCLUSION

In this paper, we have proposed IEEE 802.15.4 with RTS/CTS that utilizes the packet concatenation feature for WSNs. The use of the RTS/CTS mechanism improves channel

efficiency by decreasing the deferral time before transmitting a data packet. The proposed solution has shown that even for the case with retransmissions if the number of TX packets is higher than 5 (i.e., the number of aggregated packets), IEEE 802.15.4 with RTS/CTS and the application of packet concatenation, achieves higher throughput values in comparison to IEEE 802.15.4 with no RTS/CTS. It is a worth nothing that retransmission process does not include the backoff phase like in IEEE 802.15.4 basic access mode (i.e., $BE = 0$).

ACKNOWLEDGMENT

This work was supported by the Ph.D. FCT grant FRH/BD/66803/2009, the European Social Fund (ESF), by PESt-OE/EEI/LA0008/2013, Marie Curie Reintegration Grant PLANOPTI (FP7-PEOPLE-2009-RG), OPPORTUNISTIC-CR, PROENERGY-WSN, CREaTION, COST IC0905 "TERRA", COST IC0902 and COST IC1004 and EDULL "Archimedes III".

REFERENCES

- [1] P. Barontib, P. Pillaia, V. Chooka, S. Chessab, A. Gottab and Y. Fun, "Wireless sensor networks: A survey on the state of the art and the 802.15.4 and ZigBee standards", *Computer Communications*, vol. 30, no 7, pp. 1655-1695, May 2007.
- [2] "IEEE 802.15.4 Working Group for WPAN", <http://www.ieee802.org/15>, Sep. 2013.
- [3] J. Mizuguchi, M. Murata and W. Uemura, "A broadcasting method based on RTS/CTS for an ad-hoc network, in *Proc. of the 15th IEEE International Symposium on Consumer Electronics (ISCE 2011)*, Singapore, Singapore, Jun. 2011, pp. 104-106.
- [4] D. Jingshan, Z. Yiqun and M. Lixiang, "An adaptive RTS/CTS mechanism in IEEE 802.15.4 for multi-hop networks", in *Proc. of the International Conference on Computational Problem-Solving (ICCP 2012)*, Leshan, ROC, Oct. 2012, pp. 155-159.
- [5] P. Chatzimisios, AC Boucouvalas and V. Vitsas "Effectiveness of RTS/CTS handshake in IEEE 802.11a wireless LANs", *IEE Electronics Letters*, vol. 40, no 14, pp. 915-916, Jul. 2004.
- [6] P. Chatzimisios, A.C. Boucouvalas and V. Vitsas, "Optimisation of RTS/CTS handshake in IEEE 802.11 Wireless LANs for maximum performance", in *Proc. of the IEEE Global Telecommunications Conference (Globecom 2004) Workshops*, Dallas Texas, USA, 29 Nov.- 3 Dec. 2004, pp. 270-275.
- [7] N. Barroca, F. J. Velez and P. Chatzimisios, "Block Acknowledgment Mechanisms for the optimization of channel use in Wireless Sensor Networks", in *Proc. of the 24th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2013)*, London, UK, Sep. 2013, pp. 1570-1575.
- [8] J. Rousselot, M. Aoun and R. S. Oliver, "Accurate Timeliness Simulations for Real-Time Wireless Sensor Networks," in *Proc. of The Third UKSim European Symposium on Computer Modeling and Simulation*, Neuchatel, Switzerland, Nov. 2009, pp. 476-481.
- [9] C. Buratti and R. Verdone, "Performance Analysis of IEEE 802.15.4 Non Beacon -Enabled Mode," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 7, pp. 1-6, Sep. 2009.
- [10] *Part 15.4: Wireless Medium Access Control and Physical Layer Specifications for Low -Rate Wireless Personal Area Networks*, IEEE Std. 802.15.4, Sep. 2011.
- [11] "MiXiM framework," <http://sourceforge.net/apps/trac/mixim/>, Mar.2013.
- [12] M. S. Chowdhury, N. Ullah, M. H. Kabir, P. Khan and K. S. Kwak, "Throughput, Delay and Bandwidth Efficiency of IEEE 802.15.4a Using CSS PHY", in *Proc. of International Conference on Information and Communication Technology Convergence (ICTC)*, Jeju Island, Korea, Nov. 2010, pp. 158-163.
- [13] B. Latre, P.D. Mill, I. Moerman, N. V. Dierdonck, B. Dhoedt and P. Demeester, "Maximum Throughput and Minimum Delay in IEEE 802.15.4," in *Mobile Ad-hoc and Sensor Networks*, Springer-Verlag Berlin Heidelberg, pp. 866-876, 2005.